Research Project: „Building Climate“ Conclusions and recommendations for practice

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1 Conclusions

1.1 General

Historically the subject of moisture content in structural timber elements tended to be treated from the viewpoint of how to prevent high moisture contents to inhibit decay or growth of fungi. The evaluation of damages in large span timber structures shows that cracking parallel to the grain due to low or severe changes of moisture content is among the prevalent types of damage in such structures. These cracks reduce the capacity of the cross section to transfer tensile stresses perpendicular to grain or shear stresses. Shrinkage related cracking might be less pronounced in structural elements from solid timber if the correct sawing patterns are applied. Structural elements from glued-laminated timber with large cross sections are more vulnerable in that aspect due to their reduced adaptability to changing ambient climate. Fast and/or significant changes of ambient climate can be due to the type of construction and use of the building. Locally, these changes can be intensified, e.g., around skylights or in the proximity of heating systems.

The objective of the research project was to conduct a series of long-term measurements to provide data, enabling an overview over climate conditions and resulting timber moisture contents which can occur in large buildings of different types of use. In total, 21 buildings from seven different types uf use were monitored. This includes indoor swimming pools, ice rinks, riding rinks, gymnasiums (sports facilities), production and sales facilities and agricultural buildings.

1.2 Conclusions of the long term measurement of the indoor climate and timber moisture gradient

The developed measurement system proved to be suitable to realize long-term measurements of timber moisture content and climate conditions in buildings with timber structures with an accuracy of ±0.5 %. Of the 21 monitored objects, each featuring two points of measurement, only the indoor swimming pools led to malfunctions of the climate sensors and one problem in the reading of data from the data logger. The defective components of the climate sensors on which an onset of corrosion was noticed were replaced, but malfunctioned again shortly after. It is assumed, that the defects are the result of the very aggressive, chlorous climate of indoor swimming pools. A possible solution to this problem was to use more robust digital climate sensors and to encase the measurement system in a housing.

In order to validate the findings of the first research project, the follow-on project „Building Climate – Validation" continued the long term measurements of the climate and the resulting timber moisture content in selected buildings with heavily fluctuating conditions. From the seven original types of use with 21 buildings, five were selected. Two buildings from each of these categories were further monitored. Indoor swimming pools and gymnasiums (sports facilities) were excluded from the follow-on project due to their steady climate and independence from the outdoor conditions. Updating the existing measurement system based on the findings of the first research project was another main objective. Assumptions for the evaluation of the data were replaced by measured parameters. The distribution of the material temperature along the timber cross-section which is needed for the temperature compensation of the measured timber moisture content was determined through two additional temperature sensors inside the beam. In the first research project, the temperature distribution was calculated from the surface temperature. A comparison of the two methods for determining the material temperature showed a non-negligible discrepancy. The temperature compensation with cross section temperature curves calculated from the air temperature resulted in timber moisture gradients with smaller and fewer jumps and short time changes. When using the temperatures from the two sensors embedded 20 and 40 mm within the beam, significant jumps in the timber moisture curve were found during times of exposure to direct sunlight. These jumps were in the range of 1.5 % moisture content. The reason for this discrepancy was narrowed down with two studies. In one, it was determined that a significant portion of thermal energy from direct sunlight was being transmitted through the sensor's cable cross section to the measurement location inside the beam. This lead to an overestimation of the material temperature. Measuring the material temperature from the opposite side of the beam which was not exposed to the sun provided realistic values.

The second study confirmed through laboratory experiments that the applied analytical method to compensate the influence of the temperature on the timber moisture content leads to results within the expected accuracy. Calculating the temperature distribution within the cross section of timber beams with the Euler method with air temperatures in the vicinity of the points of measurement of moisture content leads to realistic results with an acceptable accuracy.

1.3 Conclusions from the measurement results

During the two measurement periods from October 1st 2010 to September 30th 2011 and April 1st 2013 to March 31st 2014 over 3.6 million values were recorded and analyzed with a program specifically developed for this purpose. From the indoor climate, the equilibrium moisture content was calculated and superimposed on the timber moisture curves. The moisture content could be measured at different depths of the timber cross-section through the use of sensors of different length. A graph of the moisture content over the cross-section was created for each point of measurement. This allowed for a readout of the scale of the moisture gradient as well as the difference in moisture content between the beam surface and its center. Both parameters are the basis for determining the amount of the moisture induced stress and the potential risk for crack formation.

A comparison of the results from the different types of use reaffirms the wide range of possible climate conditions (temperature, relative humidity) in buildings with timber structures. The results show an average timber moisture content between 4.4 % and 17.1 % for all types of use. The moisture gradients show a clear dampening effect and delayed adaptation to the surrounding climate at larger depths. The resulting difference in moisture content across the cross-section along with the shrinkage and swelling properties of wood can lead to internal stresses.

The moisture gradients in the group of buildings with insulation and air-conditioning are lower, compared to the group of buildings where the seasonal weather fluctuations have a larger influence on the inside climate conditions.

Indoor swimming pools fall into the first group. These types of buildings proved to have a very constant climate with conditions which are not harmful in regard to the equilibrium moisture content of timber structures. Exceptions to this are transition zones to the outside, where due to the lower temperatures, very high relative humidity with heavy fluctuations can occur. Gymnasiums (sports facilities) can also be placed in this group of buildings (closed, insulated and air-conditioned). They showed a constant yet dry climate, especially in areas with exposure to direct sunlight such as skylights. These statements also apply to sales facilities. Production facilities can have varying climate conditions depending on the specific type of use. Therefore, the climate boundary conditions must be determined individually for each structure. However, these types of buildings are mostly exposed to a constant and dry climate. Some of the buildings in this group showed large shrinkage cracks in the timber elements of the roof. The most critical period for cracks due to shrinkage will most likely be the first winter after construction. The mean indoor temperature for this group of insulated and heated buildings is ≥ 20°C (about 30°C for indoor swimming pools) and the relative humidity < 50%. The resulting timber moisture contents were in the range of 6 – 10 % with annual maximum amplitudes of 2 % (see Table 1).

Table 1: Indicative values for the monitored insulated and heated buildings during normal use, derived from data across the entire measurement period.

Category		Timber Moisture Content mean [%]	Timber Moisture Content max. A [%]	Temperature mean [°C]	rel. Humidity mean [%]
A	Swimming Pools	8,5	1,5	30	< 50
D	Gymnasiums (ports facilities)	8-10	2	20	< 50
E	Production and Sales	6,5	< 2	20	< 40
Ø	Insulated and Heated	6-10	< 2	> 20	< 50

The second group of buildings (partially open, non-insulated, non-heated buildings) includes indoor riding rinks. The climate inside these is heavily dependent on seasonal changes. During winter the combination of cold air and humidity introduced by the sprinklers, frequently results in condensation. Similarly, agricultural facilities are also affected by seasonal changes with an increased relative humidity through livestock. Similar to riding rinks, infiltrating cold outside air in combination with the increased humidity leads to high timber moisture contents and condensation. As in other buildings under a strong influence of the outside climate, the timber moisture content fluctuates heavily which, due to the seasonal character, results in noticeable, yet not exceptionally high moisture gradients. The determined mean timber moisture contents in warehouses fall within the range of 9.5 % to 14 %. However, in this research project warehouses also showed the highest seasonal indoor climate fluctuation partially due to the stored items.

Table 2: Indicative values for the category partially open, non-insulated and non-heated buildings during normal use, derived from data across the entire measurement period.

Category		Timber Moisture Content mean [%]	Timber Moisture Content max. A [%]	Temperature mean [°C]	rel. Humidity mean [%]
C	Riding Rinks	16	4	12	> 75
F	Agricultural facilities (Livestock)	15	4	13	70
G	Warehouses	12	4	11	60-75
Ø	Non-Insulated, Non-Heated	12-16	4	12	> 65

Temperatures in partially open, non-insulated and non-heated building averaged in the range of 10° - 15° C with a relative humidity above 65 %. The average moisture contents of these buildings were in the range of 12 – 16 % with annual amplitudes of about 4 % (see Table 2).

The climate in ice rinks is also subject to seasonal fluctuations due to the outside conditions and, more importantly, through the type of use. On average the mean relative humidity of closed, air-conditioned and non air-conditioned ice rinks lies between 60 % and 70 % with use related temperature fluctuations. The timber moisture content above the ice with a mean value of 15.5 % is 1.5 % higher compared to areas on the edges of the rink. The timber moisture amplitude is around 3.5 % (see Table 3). In general, the timber moisture content in indoor ice rinks is rather high and fluctuates heavily. The largest change in the building climate and timber moisture gradient resulted from the ice preparation after the summer break.

Table 3: Indicative values for the category indoor ice rinks, derived from data across the entire measurement period.

Ice Rinks		Timber Moisture Content mean [%]	Timber Moisture Content max. A [%]	Temperature mean [°C]	rel. Humidity mean [%]
B	Above Ice	15,5	3,5	10	60-70
	Above Tribunes	14			

In addition to the previously described, use-dependent climate conditions and their influence on timber moisture content and the potential for crack initiation, the results of the research project identify another important aspect. Temporary interventions, such as renovations or changes of use (temporary or permanent) can lead to major changes in climate conditions, which are reflected in distinct changes in timber moisture content. Within this research project strong drying of timber elements (temporary conversion of an ice rink and renovation of an indoor swimming pool) as well as strong moistening of very dry timber elements (conversion of a former metal-processing production facility) was observed. This results in a major increase in potential for damage due to e.g. crack initiation in glued-laminated timber elements. Accordingly, care should be taken during such interventions to realize a decelerated change of ambient climate.

2 Recommendations

The reaction of wood to moisture forms an integral part of any task in connection with this natural and renewable building material. In the following, suggestions are grouped according to their respective implementations.

2.1 Planning / New construction

The average moisture contents in heated and insulated buildings (e.g. swimming pools, gymnasiums, production and sales) were in the range of 6 – 10 % with annual amplitudes of about 2 %. Due to these relatively constant but dry conditions it should be ensured already during production, transport, installation and construction site operation that the moisture content of (especially large-volume) timber elements differs by only a few percent of the expected equilibrium moisture content ($u \leq 10\%$). Possible measures include a coordinated construction regime (e.g. preventing wetting during prolonged storage, reduction of unnecessary construction moisture). In the design of such structures it should be aimed at avoiding a restriction of free shrinkage and swelling of the components (e.g. due to fasteners at large distances perpendicular to the grain, or reinforcement placed at small distances).

In buildings with an increased influence of the outside climate (e.g. riding rinks, agriculture, warehouses), the application of insulation on the roof could help to dampen the strong changes of indoor climate and correspondingly the timber moisture gradients. In the case of partly open buildings, the effect of such measures is reduced with increasing amount of permanently open areas in the building envelope. Timber structures in areas exposed to direct sunlight (e.g. below skylights) or in the proximity of exhausts of air ventilation, should be given attention with respect to potential crack initiation due to rapid drying after a period of increased humidity. In areas with strong but periodic changes of moisture content, protective covering in the form of panel materials could be another feasible measure. The last-mentioned possibility is momentarily being investigated and measured in a separate research project carried out by the authors in collaboration with the Studiengemeinschaft Holzleimbau e.V.

2.2 Type of use / Changes in Use

The most critical period with regard a potential crack initiation will in most cases be the first winter of operation of the building. During this period, heating systems should be adjusted to not reduce the relative humidity too fast and too strong. An artificial air humidification, e.g. in the form of evaporation ponds is another possibility to dampen the speed of drying of the structural timber elements. An alternative is a surface treatment, e.g. in the form of products which dampen the moisture absorption and release in the first years of operation of the building. Currently no concrete specifications of applicable products can be given for such a surface treatment.

The influence of the type of use on the indoor climate is noticeably lower in partially open, non-insulated and non-heated buildings. Still, different measures can reduce the development of a high relative humidity. In riding rinks, the combination of cold air and humidity introduced by the sprinklers, frequently results in condensation. To reduce this effect during the cold season the sprinklers should only be used when it is absolutely necessary for the equestrian sport. In warehouses care should be taken to prevent an additional introduction of moisture into the building through the stored goods. In ice rinks, the largest change in the building climate and timber moisture gradient resulted from the ice preparation after the summer break. By air conditioning the buildings, this effect can be significantly dampened.

In addition to the previously described, use-dependent climate conditions and their influence on timber moisture content and the potential for crack initiation, the results of the research project identify another important aspect. Temporary interventions, such as renovations or changes of use (temporary or permanent) can lead to major changes in climate conditions, which are reflected in distinct changes in timber moisture content. Within this research project strong drying of timber elements (temporary conversion of an ice rink and renovation of an indoor swimming pool) as well as strong moistening of very dry timber elements (conversion of a former metal-processing production facility) was observed. This results in a major increase in potential for damage due to e.g. crack initiation in glued-laminated timber elements. Accordingly, care should be taken during such interventions to realize a decelerated change of ambient climate. The use of remedial measures (e.g. in form of evaporation basins or surface treatment) could also be a means to realize a dampened and controlled change of moisture content. Ideally, such interventions should be accompanied by expert personnel.

2.3 Examination in case of damage

When appraising damaged timber structures it is important to closely examine the climate boundary conditions and the resulting timber moisture content of the structure. If the structure proves to have different climatic boundary conditions, multiple timber moisture measurements must be carried out at varying depths and locations. In most cases, knowledge of the current timber moisture distribution is not sufficient in order to determine the cause of the damage. Therefore, the moisture history of the structure should be examined. This can be done through inspection and construction diaries. In cases where no documents exist, user surveys can give information on the climate conditions such as temperature and relative humidity.

With respect to refurbishing climate related cracks, experts have not yet found an agreement on the appropriate time to fill and close cracks. In this context, multiple influences must be taken into account such as the superposition of stress before and after the repair, the possible continuation of the crack formation on the structure's surface or within, the inhomogeneous distribution of the strength and stiffness properties perpendicular to the grain across the width of the lamella (usually stiffer inside) as well as the difference in speed of timber moisture intake and release. In order to make reliable statements regarding the correct time to repair cracks, further research and practical experiments are necessary. The climate boundary conditions gathered during this research project can be used as a basis for such further investigation.

2.4 Recommendation for the implementation in standards, guidelines and textbooks

The findings presented imply that designers should be given more information and guidance on how to treat the subject of timber moisture content during construction, use, temporary interventions and change of use of their specific building. A potential implementation of the conclusions presented would be to include such information in textbooks or commented versions of codes, highlighting the benefits of using timber elements which feature a moisture content mirroring the expected average moisture content. To increase the awareness toward specific climates it should be considered to include examples of classification of buildings of specific use into Service Classes (e.g., riding rinks, ice-skating halls) in textbooks or commented versions of codes. At the same time it should be stated that the expected average moisture content is to be determined individually for each building. Another important objective is to increase awareness toward dry climates. It would be worthwhile to consider including a note in the code stating that the average moisture content of softwoods in heated and insulated buildings (Service Class 1) will in most cases be below 10 %.